Renewable and Sustainable Energy Reviews 15 (2011) 833–838

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Development and economic assessment of a grid connected 20 MW installed capacity wind farm

Shafiqur Rehman *, Aftab Ahmad, Luai M. Al-Hadhrami

Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 13 May 2010
Accepted 2 September 2010

ABSTRACT

The study presents the design and economic assessment of a wind farm of 20 MW installed capacity, located in the Eastern region of Saudi Arabia. The wind farm is designed using 2 MW size wind machines from Vestas at a hub-height of 60 m using specialized WindFarm software. The land area is considered as flat and away from airports, habitats, hospitals, and communication towers. The energy yield and the wake losses were obtained from the energy yield module of the software for the wind farm. On-site data was collected for a period of 1 year and historical meteorological data was obtained from nearby station were utilized in the design of the proposed wind farm. The proposed wind farm could generate 59,037.7 MW h of electricity annually with plant capacity factor of 33.7%, excluding the wake losses of 3.48%. With prevalent wind turbine and other equipment costs, installation, civil works, balance of plants and operation and maintenance costs, the proposed wind farm could produced the energy at US¢ 2.94 per kW h. This study clearly indicates that grid connected wind farms could be developed in and around the measurement site.

Contents

1. Introduction

Wind is a free, clean and renewable source of energy which will never run out. Hence, generating electricity from the wind is considered economical as well as environmentally friendly. The wind energy industry is growing at a rapid pace and is set to expand globally as a source of cleaner and more sustainable power generation. Wind turbines are becoming cheaper and more powerful with larger blade lengths erected at high towers which can utilize more wind.

The energy security and the environmental damage, due to the utilization of the fossil fuels, are the two main issues facing the energy sector these days. Also, providing electricity to remote locations is a critical task faced both by the developed and developing countries. It has been recognized that the long distances and relatively small energy demands in the remote areas make electricity transmission and distribution costs prohibitive. Therefore, renewable energy resources such as the wind and solar are the most efficient option for making electricity available

* Corresponding author. Tel.: +966 3 8603802; fax: +966 3 8603996.
E-mail address: srehman@kfupm.edu.sa (S. Rehman).
URL: http://faculty.kfupm.edu.sa/ri/srehman

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doi:10.1016/j.rser.2010.09.005

to the billions of people that presently do not have access to it. Due to recent advancement in technology and competitive costs of generation of electricity from wind and solar photovoltaic, use of renewable sources of energy is being encouraged these days. To generate electricity from wind, the wind farms could be erected within months which require minimal operation and maintenance cost.

The renewable electricity generation capacity has reached an estimated 240 gigawatts (GW) worldwide in 2007, an increase of 50 percent over 2004 as a result of increasing environmental awareness and technological advancement [1]. In 2007, wind power capacity increased by a record-breaking 20,000 MW [2], bringing the world total to 94,100 MW which is enough to satisfy the residential electricity needs of 150 million people. The cost of onshore wind power has decreased by more than 80 percent since the early 1980s to roughly 7¢ per kilowatt-hour at favorable wind sites [1]. Driven by concerns regarding climate change and energy security, one in every three countries now generates a portion of its electricity from wind, with 13 countries each exceeding 1000 MW of installed wind electricity-generating capacity [World Watch Institute, 2008]. The cumulative global wind power installed capacity reached 120,791 MW at the end of 2008. With 25,170 MW installed capacity USA lead the way while Germany, Spain, China, India, and Italy followed the trends with 23,903 MW, 16,754 MW, 12,210 MW, 9645 MW and 3736 MW installed capacity as of December 2008 [3].

The various studies related to assessment of wind resource and development of wind farms have been carried out for the Middle East and African countries and reported in the literature [4–12]. El-Osta and Califa [4] carried out feasibility study for a wind farm of 6.0 MW capacities in Zwara, Tripoli, Libya. The results of the study showed that the project is economically feasible. Marafia and Ashour [7] carried out an economical feasibility study and assessment of the potential of off-shore/on-shore wind energy as a renewable source of energy in Qatar. The results of the study indicate the suitability of utilizing small to medium-size wind turbine machine. Ucar and Balo [12] carried out technical assessment for generation of electricity from four different sizes of wind turbines (De-Wind) for six different locations. The annual energy output and capacity factor for the four turbines were calculated. The capacity for the turbines varied between 0.24 and 52 for the locations studied.

Moran and Sherrington [13] carried out study on the economic feasibility of a large scale wind farm project in Scotland. Krokoszinski [14] conducted project on the efficiency and effectiveness of Wind Farms development. According to the study, the operation and maintenance (O&M) cost is the key to the economic viability of large offshore wind farms planned worldwide. Herman et al. [15] conducted study on the development of large wind turbine for the design of 500 MW offshore wind farm. The study shows that the project included the design and testing of a 2.75 MW NEG Micon prototype machine, which has been erected at the ECN Wind Turbine Test Farm Wieringermeer in February 2003.

Most of the studies carried out and reported in the literature [16–21] for Saudi Arabia are related to the wind resource assessment. Therefore, the main objective of the present study is to design a 20 MW onshore wind farm for a site in Juaymah, Saudi Arabia using Resoft Wind Farm Design Software. The measured wind data for a period of 1 year will be utilized in the design of the proposed wind farm.

2. Data, site and software description

The meteorological data (wind speeds, wind direction, air temperature, relative humidity, surface station pressure, global solar radiation) were collected at Juaymah for a period of 1 year. The data collection was done through on-site visits and remotely using Al-Jawal GSM data services. The latitude, longitude and altitude of the measurements site were 26°47.706′N, 49°53.719′E and 0.0 m.

Table 1
Summary of meteorological data collected at Juaymah for the year 2007.

Meteorological Parameters	Mean	Min	Max	Std. dev
Wind speed at 10 m, m/s	4.14	0.4	15.9	2.3
Wind speed at 20 m, m/s	4.84	0.4	17.8	2.36
Wind speed at 30 m, m/s	5.34	0.4	18.4	2.5
Wind speed at 40 m, m/s	5.69	0.4	20	2.53
Wind direction at 30 m, degrees	202.9	0.0	356	116.3
Wind direction at 40 m, degrees	205.4	0.0	356	121.9
Air temperature, °C	26.09	2.5	49.6	9.23
Solar radiation, W/m^2	201	0.0	1043	273.0
Barometric pressure, mbar	1014	995	1032	8.0
Relative humidity, %	17.3	0.0	100.2	23.5

The data collection site at Juaymah is an open area from all directions except a number of transmission line poles and cables. The site is located inside the Juaymah power plant and is fenced and secured. Data were recorded every 10 min on a removable data storage card. The wind speed data were collected at 10, 20, 30, and 40 m height above the ground. At 10 and 20 m heights only one sensor was installed. At 30 and 40 m heights two sensors were installed. The wind direction data were recorded at 30 and 40 m. The surface air temperature (°C), and global solar radiation (W/m^2) data were also collected at 2 m above the ground surface. The summary of meteorological data collected at Juaymah is shown in Table 1.

The daily historical meteorological data was obtained from a nearby meteorological station (Dhahran, latitude 26°06′N and longitude 50°10′E and altitude 22 m above mean sea level) for a period of 39 years from 1970 to 2009 (Table 2).

The WindFarm software (from Resoft, UK) is a powerful and flexible tool that significantly enhances the wind farm development potential. It simplifies the development process of creating, analyzing, and optimizing a wind farm layout. WindFarm software can be used to calculate the energy yield of a wind farm simultaneously including topographic and wake effects; optimize the turbine layout for maximum energy yield or minimum cost of energy whilst subject to natural, planning (including noise) and engineering constraints; perform noise calculations (showing the noise contours); analyze wind turbine data; perform measure-correlate-predict analysis of wind speed data; create planning quality photomontages and animation; display wire frame views of the wind farm; and calculate shadow flicker.

3. Wind farm design and energy yield

In the present study, a flat land was considered for the development of hypothetical wind farm in Juaymah. A total of 10×9.12 km^2 area is considered for the development of wind farm of 20 MW capacity. The wind farm is designed using 2000 kW size wind machines from Vestas at a hub-height of 60 m The total of 10

Table 2
Summary of daily meteorological data obtained from PME for Dhahran for the period from 1970 to 2009.

Meteorological parameters	Mean	Min	Max	Std. dev
Wind speed at 10 m, m/s	4.4	0	12.9	1.68
Wind direction at 10 m, degrees	115.9	0	337.5	123.1
Air temperature, °C	26.39	7.4	41	7.72
Barometric pressure, mbar	1007	988	1028	8.0
Relative humidity, %	53.3	5	100	17.4

Table 3
Technical data of wind machines used in the design of the wind farm.

Wind machine	Cut-in speed (m/s)	Cutout speed (m/s)	Rated speed (m/s)	Rated output (kW)	Rotor diameter (m)	Expected life (years)
V80-2000	3.0	25.0	15.0	2000	80	20

wind machines, each of 2000 kW capacity, were put in simple geometrical configuration for wind farm layout design. The technical data of wind machines from Vestas and wind farm design layout is described in details in the sections below.

The measured 10-min average wind speed and other meteorological data for the year 2007 were used for wind farm design at Juaymah. The daily average wind speed data were taken from the historical wind data file obtained from PME for a period of 39 years between 1970 and 2009 for long term prediction of wind speed by the wind farm software.

3.1. The wind turbine

The technical data of wind machines from Vestas is given in Table 3. The cut-in-speed, at which the wind machines start producing energy, is 3 m/s as can be seen from the table. In this particular design, the hub-height is kept as 60 m. The wind power curve for a 2000 kW Vestas wind machine is given in Fig. 1. The wind power thrust coefficient curve of the machine is given in Fig. 2.

3.2. Wind farm layout design and energy yield

The wind farm layout design includes the citing of the wind machines and houses in and around the proposed wind farm development area. Fig. 3 depicts the wind farm layout obtained from Wind Farm Layout Tool of the WindFarm software, for 20 MW installed capacity using 10 wind machines of 2000 kW each. The wind machines were separated from each other by 5 times the rotor diameter and the rows were separated by 7 times the rotor diameters. The physical positions of the wind machines are shown by the diamond letter in the map for the proposed wind farm at Juaymah. Each wind turbine is identified by a number, as shown in Fig. 3. The houses in the vicinity of the wind farm are indicated by H1, H2, ... etc. The location of the anemometer is shown as A1.

The above wind farm layout in conjunction with wind rose and wind machine data files were used in energy yield module of the WindFarm Software to calculate the annual energy yield. The energy yield and the wake losses obtained from the Energy Yield module of the software for a wind farm of 20 MW installed capacity are given in Table 4.

To study the effect of noise produced by the wind turbines on the nearby houses, the noise calculation module of the WindFarm software was used to obtain the noise contours for the wind farm. The resulting noise contours are shown in Fig. 4. As can be seen from the contours, the noise produced by the machines is within the permissible limit.

3.3. Photomontage

The photomontage and wire frame module of WindFarm displays perspective views of the landscape and the wind turbines. The height data specified with the project is used to create the wire frames, with the default region being the wind farm map region in WindFarm Designer. When a photomontage run file is created there must be an associated photograph, which is used as a background to the wire frame display. In this mode, the turbines can be rendered to provide a photo-realistic impression of the wind farm. The turbines can also be animated using an animation player provided with the software to show the animations and photomontages. Fig. 5 shows a close-up view of a 20 MW installed

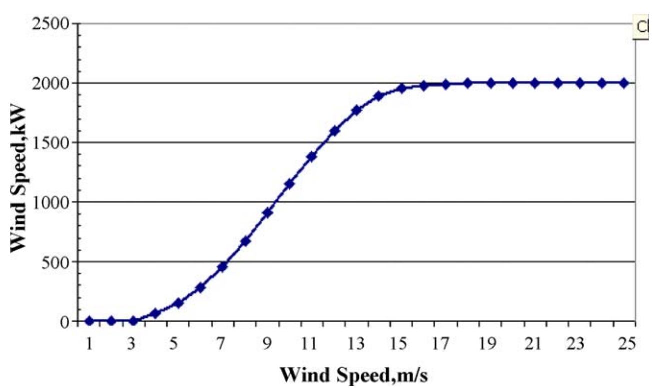

Fig. 1. Wind power curve for Vestas 2000 kW wind machine used in the design of wind farm at Juaymah.

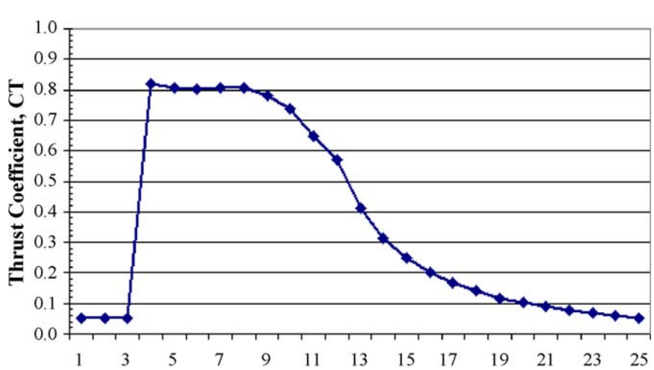

Fig. 2. Wind power thrust coefficient curve for Vestas 2000 kW wind machine.

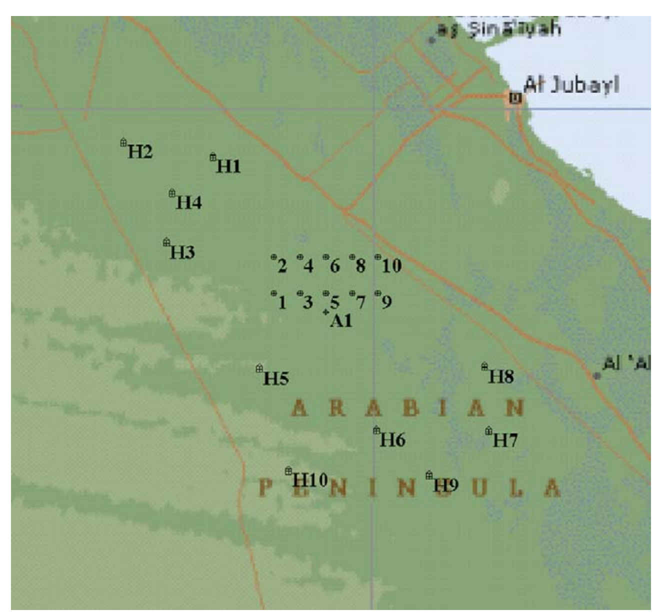

Fig. 3. Layout for a wind farm of 20 MW installed capacity.

Table 4
Annual energy yield from a 20 MW wind farm at Juaymah.

Wind direction	Total energy field			
	Base yield	Topographic effects	Wake losses	Total yield
	GW h	% Change	% Loss	GW h
0.00	17.0927	0.00	−5.91	16.0822
22.50	9.2796	0.00	−1.26	9.1625
45.00	2.5253	0.00	−4.73	2.4058
67.50	2.0474	0.00	−2.41	1.9981
90.00	0.7067	0.00	−25.08	0.5294
112.50	0.4829	0.00	−2.25	0.4720
135.00	1.3628	0.00	−3.47	1.3155
157.50	3.5901	0.00	−0.99	3.5546
180.00	0.3818	0.00	−9.32	0.3462
202.50	0.6232	0.00	−1.29	0.6152
225.00	0.5166	0.00	−4.16	0.4951
247.50	0.7516	0.00	−1.40	0.7410
270.00	0.8509	0.00	−17.70	0.7003
292.00	1.0328	0.00	−1.70	1.0512
315.00	4.2258	0.00	−3.16	4.0920
337.50	15.6959	0.00	−1.17	15.5125
Total	61.1660	0.00	−3.48	59.0377

capacity wind farm which was developed using 10 WECS of 2000 kW each from Vestas at Juaymah. The photomontage view of the wind farm, Fig. 5, shows 5 turbines visible in the picture out of a total of 10 turbines. Viewing of the turbines depends on the view point from where one is looking at the wind farm.

4. Economical analysis

In the early 1980s, the wind-generated electricity cost was as much as 30 cents per kilowatt-hour [22]. Now wind power plants at excellent sites are generating electricity at less than 5 cents/kW h [22]. The capital cost is high, however, being between 75% and 90% of the total project costs [23]. The major factors which affect the cost of electricity generated from the wind include the availability of the wind, micro-siting of the turbines, and the

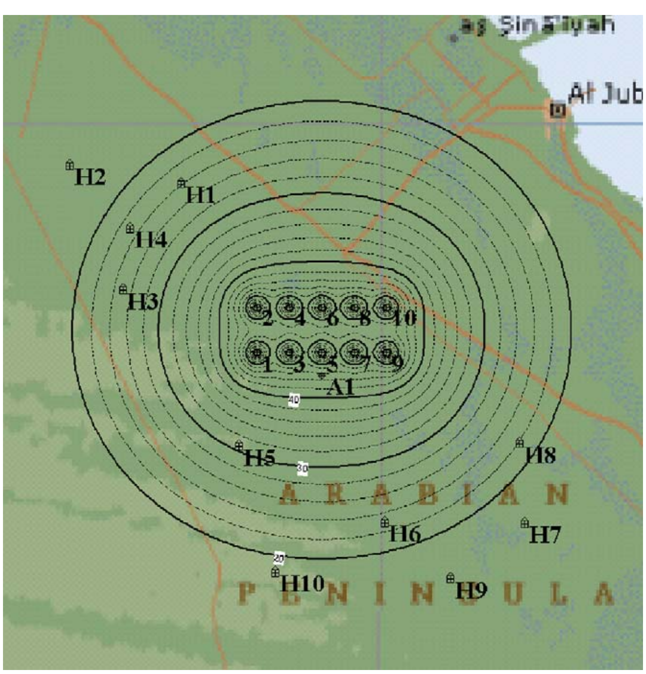

Fig. 4. Noise contours for Juaymah 20 MW wind farm.

Fig. 5. A close-up photomontage view (not all turbines visible) of a developed 20 MW installed capacity wind farm using 10 WECS of 2000 kW from Vestas.

inherent nature of the wind turbines which depend on varying wind speed to generate power. The financial factors include the rate of return on the capital and the length of time over which the capital is repaid. Of all these factors the most important is the intensity of the wind. The maintenance cost is generally very low when the turbines are brand new and ranges from 1.5 to 2 percent per year of the original turbine investment. The components of wind turbines are usually designed to last 20–30 years. In practice, wind turbines need servicing and inspection once every 6 months to ensure their proper operating conditions.

The economics of a wind energy conversion (WEC) system depends mainly on the operator specific boundary conditions. A simplified approach to calculate the cost of electricity per kilowatt-hour includes investment, operation and maintenance, and capital cost. The investment cost includes the cost of WEC, foundation, grid connection, planning, engineering, licensing, and other unforeseen. The operation and maintenance cost include the repair, insurance, monitoring, and management, while the capital cost consist of interest and repayment of debt. In order to calculate the present value of cost (PVC) of electricity generated per year, the following expression, given by Lysen [24] and referred by Alnaser [25], Habali et al. [26], and Rehman et al. [20] is used in the present study:

$$\mathrm{PVC} = I + \mathrm{Comr}\left(\frac{1+i}{r-i}\right) \times \left[1 - \left(\frac{1+i}{1+r}\right)^{n}\right] - s\left(\frac{1+i}{1+r}\right)^{n} \qquad (1)$$

In this equation, "I" is the investment cost of the wind machine, balance of plant and the transmission; n is the life of machine; "Comr" is the operation and maintenance cost; "s" is the scrap value (10% of the capital cost excluding the civil construction and cable cost); "r" is the discount rate (10%), and "i" is the inflation rate (6%).

Various other cost elements, which comprise the balance of plant costs, are assumed based on literature, estimates from local consultants or contractors, or estimates by the project team members and are summarized in Table 5. This table provides the rates in \$/unit and the total cost of each element for a wind farm of 20 MW installed capacity proposed to be developed using 10 wind machines of 2000 kW each from Vestas. The design of foundation is

Table 5
Balance of plant cost elements for a proposed wind farm of 20 MW capacity.

Cost items	Rate	Cost (\$)
Paved road[a]	\$16 per m^2	460,800
Un-paved road[b]	\$10 per m^2	180,000
Tower foundation	\$60,000 per WECS	600,000
Control systems	\$2000 per MW	40,000
Engineering and overheads	Lump sum	500,000
Control building – 300 m^2	Lump sum	150,000
Other buildings – 700 m^2	Lump sum	350,000
Initial supplies	Lump sum	200,000
Total		2,480,800

[a] Length of paved double road was assumed to be 4 km (28,800 m^2).
[b] Length of un-paved single road was taken as 5 km (18,000 m^2).

Table 6
Wind machine costs for proposed wind farm.

Cost items	Unit cost ($)	Cost of 10 WECS
Turbine	1,800,000	18,000,000
Delivery	70,000	700,000
Total	1,870,000	18,700,000

Table 7
Electrical infrastructure initial capital costs for proposed wind farm.

Cost items	Rate	Cost ($)
Sub-station	–	8,000,000
Converter AC to DC	$200 per kW	4,000,000
Transformer	$15,000 per unit	150,000
Underground cable[a]	$133,000 per km	598,500
Overhead line[b]	$266,670 per km	1,333,350
Total		14,081,850

[a] Length of underground cable was taken as 4.5 km.
[b] Length of overhead line was assumed to be 5 km from the wind farm.

based on the static weight of the nacelle, weight of rotor, weight of the tower, and the dynamic wind load for a survival speed of 65 m/s. The civil construction also included the cost of a control building for housing computing facilities, control devices, regularly required inventory items, and space for human occupancy. The cost of a 2000 kW machine including the tower, obtained from an Internet website [27] was US $1,800,000. The transportation cost of the wind machine, given in Table 6, is assumed to be US $70,000 per machine. The costs of electrical infrastructure and transmission system elements are given in Table 7.

In order to calculate the cost of energy (COE) in US¢/kW h, the net present value of cost (PVC) was calculated using all the cost elements described in previous paragraphs and Eq. (1). The COE was obtained by dividing the NPV by the total energy yield expected from the wind farm over the life time of the wind farm. A simple program was developed in MS Excel sheets to perform the cost calculations.

5. Results and discussion

The state of the art WindFarm software was used to estimate the energy yield from a wind farm of 20 MW installed capacity at the site of measurements. For long-term wind patterns in the area, the historical meteorological data was also used as one of the input to the software along with the site measurements. Table 4 provides details of the wind energy yield in different wind direction and respective wake losses. About 76% of the energy production was caused by the winds blowing from the NW and NNE direction i.e.

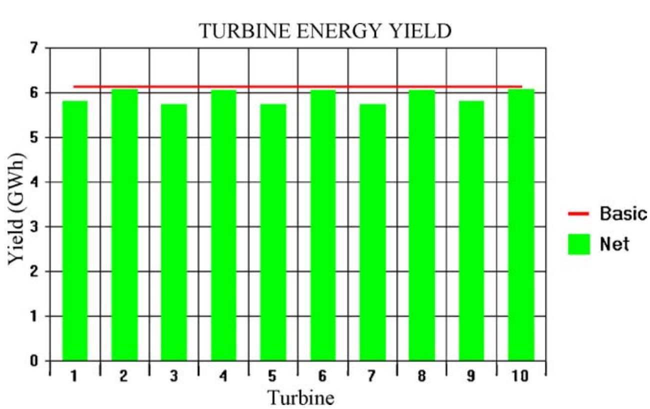

Fig. 6. Energy yield from each wind machines at Juaymah wind farm of 20 MW installed capacity.

Table 8
Sensitivity analysis: effect of wind turbine life and plant capacity factor on present value cost and the cost of energy for an inflation rate of $i = 6\%$ and discount rate of $r = 10\%$.

S. no.	WECS life (years)	PCF (%)	PVC (US$)	COE (US¢/kW h)
1	20	33.7	34,726,688	2.94
2	25	33.7	35,108,520	2.38
3	30	33.7	35,425,796	2.00
4	20	25	34,726,688	3.96
5	20	30	34,726,688	3.30
6	20	35	34,726,688	2.83
7	20	40	34,726,688	2.48

between 315 and 22.5 degrees, as can be seen from Table 4. The percent total wake loss for the wind farm was 3.48%. Higher wake losses of about 25% and 18% were observed during the period when wind was blowing from 90 to 270 degrees. The net annual energy produced from wind farms was 59.037 GW h and the plant capacity factors (PCF) was 33.7%.

The expected annual energy yield from each turbine is shown in Fig. 6. The wind turbines number 2, 4, 6, 8 and 10 produced the maximum energy while the others produced a bit less, as can be seen from the figure. It may be explained that at the wind farm location, the wind was flowing most of the time from NW and NNE direction, so the first row of the wind machines received the maximum wind intensity and hence produced the maximum energy compared to wind turbines in the following row.

The PVC and COE obtained for proposed wind farm 20 MW installed capacity at Juaymah is summarized in Table 8. The PVC and COE were calculated for varying plant life and plant capacity factors. The values of COE in Table 8 showed a decrease in COE with increase in plant life and PCF. With 20 years of plant life and a PCF of 33.7%, the proposed wind farm could produce energy at 2.94 US¢/kW h while for same plant life but a lower PCF of 25% the COE was found to be 3.96 US¢/kW h.

6. Concluding remarks

The present study has clearly indicated that wind farm development and its utilization in the area of present study is feasible both technically and economically and requires due attention from the policy makers and the investors. Specifically, the above statement is justified due to the availability of high wind speeds of 5.69 m/s at 40 m above ground level on annual basis, higher wind intensities during day time hours and during summer time which favors the high energy demands in this part of the world.

Acknowledgements

The author wishes to acknowledge the support of The Research Institute of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

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